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RESEARCH AT THE STANFORD CENTER FOR RADAR ASTRONOMY

INTRODUCTION

The Stanford Center for Radar Astronomy (SCRA) is a joint venture of Stanford University (SU) and the Stanford Research Institute (SRI) to facilitate cooperative efforts (scientific, engineering, and graduate student training) in radar astronomy and space science. The common interest in this field has grown out of basic and applied research programs at both groups for radar studies of the upper atmosphere and interplanetary space.

NASA grant NsG-377 funds have been used for a number of theoretical and experimental investigations in radio and radar studies of space plasmas (the interplanetary medium, the earth's magnetospheric wake, the solar corona, planetary ionosphere, etc.), lunar and planetary surfaces, communication theory, and spacecraft instrumentation. In addition, a number of research projects with separate support have grown out of work started under this grant. These include separate projects on: (1) a study of the polarization, power, and spectra of burst noise from Jupiter and the sun (now funded by NSF); (2) the radio propagation experiment on Pioneer spacecraft, A through E; (3) the S-band occultation experiment on Mariner IV, in support of the JPL effort on the same subject; (4) the dual-frequency radio propagation experiment for Mariner-Venus 1967; and (5) the lunar surface and occultation experiments based on receiving the telemetry signals from AIMP spacecraft. Other proposals are pending for radio propagation experiments on Mariner 69, Voyager, and Lunar Orbiter, and for a theoretical study of relativistic effects in space probe tracking. Initial work in all these areas was also started and some aspects are still continuing with grant support under NsG-377.

While the number of new projects spawned by the grant is certainly a valid measure of its vitality and importance, it is by no means the only measure. In particular, experimental monostatic radar astronomy studies of the moon and sun have been conducted with this support, and a number of theoretical studies by graduate students on communication theory, spacecraft instrumentation, and new methods of planetary surface studies have been completed. Under the broad support offered by the grant, we attempt to make good use of the fact that there is no specific goal in mind, but rather we are relatively free to explore a number of concepts and ideas that, while they may or may not prove to be of importance in later space projects, they appear to be potentially important in the general area of space science and exploration.

PLANETARY RESEARCH

Monostatic Radar Astronomy

The most important current result is the new series of measurements which have been made of the electron density and the shape of the earth's magnetospheric wake. These confirm our earlier suggestions in 1965 that the density is on the order of 150 electron cm^{-3}, that the wake extends at least as far as the moon, and that its angular size is about 90°. These results are based on dual-frequency, differential group-path (chirp radar) measurements at 25 and 50 MHz of radar echoes from the moon.

The analysis of 6- and 12-meter lunar chirp radar echoes obtained in 1964-65 is continuing to determine the nature of backscatter vs. range at these wavelengths and to fit it to the theoretical function. Although the chirp radar method yields high range resolution, the signal-to-noise ratio is not sufficient to allow detection of more than the first 400-600 μsec from the leading edge of the moon, which makes it difficult to match the data to a theoretical function with much confidence. In order to partially overcome this difficulty, more data will be averaged so as to reduce the variance in the measured echo strength-delay curve. Also, a broader range depth will be looked at to determine more accurately the background noise level, which is a critical parameter in the theoretical function fitting.

Even so, a fairly good fit was obtained for the 6 meter data using the expression $P(\theta)/P(\theta = 0) = 1/(\cos^4\theta + R \sin^2\theta)^{3/2}$ [P. Beckman, Radar backscatter from the moon, J. Geophys. Res., 70, 2345, 1965] with $R = 173$ over an interval from $\theta = 0^\circ$ to $\theta = 21^\circ$. However, this expression apparently does not adequately describe the scattering function, for both the 6- and 12-meter data show a small peak at the leading edge which may be due to specular reflection.

Since the data is derived from a chirp signal and each range therefore corresponds to a particular frequency, it is necessary to spectrally analyze the signal. This is done digitally on the Stanford Computation Center's IBM 7090. By the nature of digital spectral analysis, each estimate for the power spectral density at a particular frequency is the weighted average of the actual power spectrum through a "window" around that frequency. In order to make a comparison, a theoretical function (which is usually specified for an infinitesimal pulse) must be modified by suitably averaging it through a similar series of "windows". The fitting of the data to the modified theoretical curve (which has several parameters to determine) is also done by a digital computer which records for the minimum average percent squared error point. This technique resulted in close fits between the data and computer values (within ±1.5 db at isolated extreme deviations but much closer on the average), but more data will be analyzed to obtain more confidence in the results.

The monostatic radar program has produced a number of equipment techniques for switching at very high power levels, for measuring signal polarization, and for the precise measurement of Doppler frequency. During the past year a new, very precise method of generating linear frequency sweeps with a time bandwidth product of 10^5 was developed in cooperation with other programs. This equipment allows the 300-kw transmitter to be run as a CW chirp radar for the measurements discussed in (2) above.

In addition, an interface has been developed for the IBM 1620 computer which will sequentially sample and digitize channels of analog data. These data are then operated upon by the 1620 and stored on magnetic tape or punched cards in a form suitable for use on the IBM 7090 and an automatic plotter. This system has made reduction of lunar and solar radar data so inexpensive and rapid that it is now possible to look at all of the data in detail that would have been impossible a few years ago.

Planetary Surface Mapping

A number of important studies have been completed during the last year, one in particular could become the major experiment in future flyby and orbiting missions to Venus. This has to do with bistatic radar astronomy studies of planetary surfaces, using ground-based transmitters and spacecraft receivers. In particular, by sampling the composite direct and scattered wave at the spacecraft, it should be possible to form a two-dimensional radar reflectivity map of the planetary surface. The proposed technique is different but analogous to holography and to side-looking radar, and resolution to the order of a few kilometers on Venus should be possible (barring serious atmospheric distortion) with state-of-the-art equipment. While Venus is obviously of prime interest here, important scientific information could also be obtained by this technique for the moon, Mars, and Mercury. A planet under illumination provides a two dimensional surface when viewed at close range and the trajectory of a spacecraft is a line. Thus, it is apparently possible to illuminate a planet or the moon from the earth, sample the interference pattern with an orbiting spacecraft, and from the data recreate a picture of the surface.

The form of the optimum detector corresponding to the signal processing required for reconstructing the brightness distribution has been obtained. Optical analog simulation of the technique has verified the salient features of the theory. Work is in progress for a flight test of the method using the down link telemetry carriers for vehicles in orbit around the moon.

Present plans for the immediate future include:

1. Optical simulation of effects of noise on the processor
2. Computer simulation of processing and mapping

3. Search for simple realizations of the processor

4. Design study for flight hardware

5. Studies of planetary surface models.

Planetary Atmospheres and Ionospheres

Work starting in 1962 regarding the importance of radio occultation for the study of planetary atmospheres and ionospheres was continued under the grant in 1963 and 1964, and led first to proposals for dual-frequency occultation experiments using Mariner-Mars 64. During the past year the results of this experiment have added considerably to our knowledge of the atmosphere of Mars, and have had major effects on engineering planning for future missions to Mars, particularly landing and orbiting missions. Early grant work also led to the Pioneer 6 radio experiment, and we are just now able to give first results from this relatively direct measurement of average interplanetary electron densities (8 to 9 electrons per cubic centimeter at 1 AU, during this part of the sunspot cycle). Work conducted on the grant during the past year has also been important in defining both the S-band and dual-frequency occultation experiments for the Mariner-Venus 67 mission.

Sun Echoes

Currently, all effort is being made to complete data reduction for over 150 attempts to receive radar echoes from the sun. The most recent trials were in September 1965, but system re-evaluation and computer difficulties have delayed the results. The data reduction system however is now fully operational and reduction is nearly complete.

A large number of trials were made in the summer of 1964 but a tape recorder difficulty badly tainted the data. A procedure for removing the resultant corruption has been developed and is being used to recover the data with moderate success. When all of the data have been reduced, the results from each of the approximately 150 individual runs will be added together to form a composite result equivalent to a single run with 150 times the nominal transmitter power level. This must be done to increase the signal-to-noise ratio so that the signal can be detected, since it cannot be seen in any of the individual runs.

Ionospheric Disturbances

Dynamo electric fields are generated from the motion of conducting air across geomagnetic field lines. These fields are believed to be one of the major sources of ionospheric dynamics and geomagnetic disturbances. It has been suggested that fields in the E region, where the dynamo fields are mostly embedded, could be coupled to the F region and even higher without much loss in strength. This suggestion of coupling is based on the fact that the conductivities parallel to geomagnetic field lines are much greater than the transverse conductivities; therefore, the geomagnetic field lines connecting the E and F regions can be considered as electric equipotential lines. The validity of this suggestion is the main concern of this study.

Cases of electrostatic fields in an open but horizontally stratified ionosphere imposing geomagnetic fields, are considered. After checking its transient decaying time, it has been established that the vertical currents in the ionosphere are very small in comparison with horizontal currents. In a steady state, an analytic solution can be found for nonequatorial latitudes. The results might hint at some qualitative and quantitative idea of the coupling mechanism from the E to the F region. Applications are going to be made to attempt to explain spread-F echoes, ionization drifts, and field-aligned irregularities in the F region.

SPACECRAFT TECHNIQUES

Signal Channel Coding Schemes

A study is being conducted to realize a coding scheme for additive noise channels with feedback developed by Schalkwijk[1,2]. Under the condition of noiseless feedback, this is the first coding scheme to achieve channel capacity for the band limited channel. It is, therefore, important to examine the realizability of the coding scheme and to specify a system to achieve it.

Practical realizations can not achieve channel capacity. However, calculations have shown that if the scheme can be mechanized at all, 25 to 50% of capacity and an error probability less than 10^{-6} should be obtained. Although a general realization is being sought, particular attention is given to a system suited to space communications.

1. Schalkwijk, J.P.M., Coding Schemes for Additive Noise Channels with Feedback, Sci. Rpt. No. 10, NsG-377, SU-SEL-65-073, Stanford Electronics Laboratories, Stanford, California, August 1965.

2. Signal Channel Coding Schemes, Semi-Annual Status Report No. 6, NsG-377, Radioscience Laboratory, Stanford University, Stanford, California, January 1966, pp. 6-7.

Transmission over the channel is by double sideband suppressed carrier signals and detection is by matched filters. Useful signals and filters have been determined.

The coding scheme is an iterative process employing analog signals. At both the receiver and transmitter analog computations must be performed. These require storage of lengthy sequences of analog signals. Herein lies the chief obstacle to the realization: storage, random access, and insertion into the computations of these analog signals. It may be necessary to use digital storage and analog/digital conversions. However, this will change the statistics involved and remove us somewhat from Schalkwijk's original system description.

A possible alternative, now under study, is to develop an analogous system which transmits vectors with binary components instead of scalar (analog) values as used in the present system definition. This would permit digital storage and calculations, solving the aforementioned problems. However, the resultant system again may not lie completely within the mathematical description of Schalkwijk's original coding scheme.

The storage problem and the mechanization of the transmitter and receiver computation processes is now under study. When these areas are resolved, the whole system will be tied together and evaluated.

Receiving Techniques

During this past quarter an investigation into the application of digital techniques to receiver systems was initiated. It is hoped that much of the analog circuitry in today's receivers can be replaced with digital circuitry, thus taking advantage of the many desirable features of integrated circuits. Relevant techniques such as sampling, modulation theory, and the substitution of digital elements, (e.g. digital integrators for their analog counterparts), will be examined.

One promising technique is the production of a bandpass filter using sampling. This technique was first suggested by Franks and Sandberg of the Bell Telephone Labs. The filter consists of three parallel paths which are selected sequentially by high speed switches. Each path contains a low pass filter. Within each path, the input switch translates the information from the center frequency (f_o) down to d.c., the low pass filter determines the bandwidth, and the output switch translates the band back up to f_o. Three paths are necessary to ensure cancellation of harmonics generated by the sampling process. The switches in each path are on for one third of the total period. Thus, $f_o = 1/3\,T_s$, and if $T_s = 10\ n_s$, then $f_o = 33$ MHz. Inductance is obtainable in integrated circuits by using negative impedance converters and gyrators (suggested by R. Newcomb). These techniques work well at low frequencies and thus are ideally suited to the synthesis of the low pass filters we require. The upper limit on f_o is determined by how fast a switch we can produce. The effects of finite rise and fall times on the analysis is being investigated. A preliminary estimate of the upper limit on f_o is about 130 MHz for present integrated circuit fabrication techniques and 1.3 GHz for a discrete component version using hot carrier diodes as switching elements. In summary, this bandpass filter has the following characteristics:

1. Bandwidth and center frequency are essentially independent and Q may be made quite high, (the upper limitation of Q is given

by problems in synthesizing the low pass filters, stabilizing the center frequency, and instabilities. This will be investigated. The upper limit is probably in the range from 10^4 to 10^5.)

2. The center frequency depends on the switch period T_s and thus is electrically tunable.

3. If requirements on f_o are not too high, it may be built in an integrated circuit.

Another project currently under investigation is the development of a digital equivalent of a phase-locked loop.

Spacecraft Orientation

A study and comparison of spin axis orientation for various launch conditions was completed for a proposed Stanford University deep space probe. This probe would be launched into orbit around the sun. Since the probe has no attitude control, its spin axis orientation is determined at launch by the following five factors: launch azimuth, time of day, time of year, payload weight, and delays in the fourth stage ignition.

The desired spin axis orientation is perpendicular to the ecliptic plane. This orientation gives maximum radio signal strength to and from the spacecraft and maximum solar power from the solar panels.

Various combinations of the above five factors within the Scout rocket capability were evaluated with respect to the desired orientation. On the basis of maximum average signal power (including effects of the sun) over a 700-day probe life, the following launch is recommended:

1. A 37-lb. spacecraft

2. A polar launch at sunrise of the autumnal equinox

3. A launch ellipse which gives 4.6° range and an altitude of 140 km at third stage burnout

4. Delay spinup and firing of the fourth stage until a declination of 10° N (altitude approximately 140 km) is reached

5. A tangential orientation to the local smooth earth surface at the fourth stage spinup of the rocket.

Publications

1966 Fejfar, A., R. V. Bhonsle, and B. B. Lusignan, A Digital Radio Polarimeter, submitted to the Proc. IEEE (in press).

1966 Bhonsle, R. V., A. Fejfar, and B. B. Lusignan, Digital Polarimeter Observations of Spectral Type III Solar Decametric Bursts, submitted to the J. Geophys. Res. (in press).

1966 Fjeldbo, G., W. C. Fjeldbo, and V. R. Eshleman, The Atmosphere of Mars: A Comparison of Different Model Studies Based on Mariner IV Occultation Data, Science, 153, 1518.

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1966 Spira, P. M., Digital Measurements of Differential Time Delay of Pseudo Random Coded Signals, Sci. Rpt. no. 6, NsG-377, SU-SEL-65-027, Stanford Elec. Lab., Stanford, California, January.

Papers Presented

The following papers were given at the Spring URSI meeting April 18-21, 1966, in Washington, D. C.:

Digital Radio Polarimeter Observations of Jovian and Solar Decametric Emissions, A. Fejfar, R. V. Bhonsle, and B. B. Lusignan, Commission V.

Bistatic Radar Experiments for the Study and Mapping of the Lunar Surface, G. L. Tyler, G. Fjeldbo, and R. L. Koehler, Commission V.

Interplanetary Electron Density Measurements with the Pioneer VI Spacecraft, R. L. Koehler, Commission V.

Cislunar Electron Content as Determined by Radar Group Delay Measurements, H. T. Howard, Commission V.

Bistatic Radar Astronomy - Summary and Prospectus, V. R. Eshleman, Commission V.

Models for the Atmosphere of Mars Based on the Mariner IV Occultation Experiment, G. Fjeldbo, Commission II.